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AC LOSSES IN A $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ COIL (POSTPRINT)

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ac losses in a $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ coil

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The properties of a small pancake coil made with a 10 mm wide copper-stabilized $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) coated conductor were investigated. The radial component of the magnetic field was mapped at the coil edge in both the dc and ac regimes and differs significantly from that calculated assuming a uniform current distribution. The observed hysteresis indicates the strong influence of the ferromagnetic properties of the substrate. The ac losses of the coil were measured for ac frequencies between 60 and 1000 Hz. The differences in properties of the YBCO coil and a similarly prepared copper coil are discussed. © 2006 American Institute of Physics.

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Second generation high temperature superconductors (2G HTSs), or $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) coated conductors, are now seen as the preferred candidate for high energy density HTS applications.¹ The present focus for commercialization is the scaling of the 2G HTS production to levels that allow the construction and testing of prototype coils and cables, for both dc and ac applications. Stacks of pancake or double pancake coils are a popular way of magnet construction for winding technology reasons. However, the calculation and measurement of losses and critical currents in such coils is complicated by several factors. The magnetic anisotropy of these tapes strongly affects the distribution of the current density in intricate ways.² The critical current of a coil wound with 2G HTS is limited by the largest magnetic field component perpendicular to the tape plane.³ Also, the HTS tape located near the axial ends of the solenoidal configuration is exposed to an inhomogeneous magnetic field and the determination of the critical current is not straightforward.⁴

According to Brandt and Indenbom,⁵ the hysteresis loss in a homogeneous YBCO tape is directly proportional to the tape width when exposed to a uniform transverse magnetic field applied perpendicular to the tape plane. Amemiya *et al.* have shown that for an arbitrary orientation of a uniform magnetic field, ac losses are proportional to the perpendicular component of the field.⁶ To reduce hysteretic losses, subdividing the tape into narrow filaments is necessary.^{7,8} Sumpston *et al.* published experimental data on losses of unstriped and striped YBCO coated conductors in external magnetic fields with frequencies of 50–200 Hz demonstrating the effectiveness of striated 2G HTS.⁹ Finally, Tsukamoto showed that the nonuniform current distribution in YBCO tapes can cause a deviation of the measured losses from calculated results.¹⁰ As such, ac losses in windings made of YBCO coated conductor are expected to be quite high and difficult to assess.¹¹ This work provides initial characterization of a small pancake coil made with YBCO conductor and compares the results with those obtained on a coil made from

pure copper tape with dimensions similar to the YBCO conductor.

The 2G YBCO coil was made using a 1.2 m length of copper-stabilized YBCO coated conductor. It was cowound with wet, epoxy-saturated fiberglass cloth on a G10 coil form, and had an inner and outer diameter of 25.8 and 33.8 mm after completion. The n value was ~ 29 and the number of turns in the winding was 13. The conductor was made using a RABiTs type Ni-5 at % W substrate with a sputtered Y_2O_3 seed layer, a yttrium-stabilized zirconia (YSZ) barrier layer, and a CeO_2 cap layer.¹² The substrate had a Curie temperature of $\sim 60^\circ\text{C}$ and is ferromagnetic at 77 K.¹³ This ferromagnetism is expected to contribute to the coil's inductance, as observed in experiments with superconducting cables.¹⁴ The $0.8\text{ }\mu\text{m}$ YBCO layer was deposited using a Trifluoroacetate (TFA)-based solution process and subsequently capped with a $3\text{ }\mu\text{m}$ Ag layer to which a $50\text{ }\mu\text{m}$ thick Cu 110 foil was laminated. The copper coil was made using a $\sim 110\text{ }\mu\text{m}$ thick, 1.26 m long copper tape, 10 mm wide, with a resistivity of $1.8 \times 10^{-7}\text{ }\Omega\text{ cm}$ at 77 K. The number of turns, the inner and outer coil diameter, and insulation were the same as those of the YBCO coil. The ac losses of both coils were measured by a NORMA Power Analyzer 4000D.

The dc critical current of the YBCO coil with a slowly increasing transport current was 154 A, at $0.1\text{ }\mu\text{V/cm}$. The corresponding current density calculated for the winding cross section was $\sim 5 \times 10^3\text{ A/cm}^2$ and for the 2G conductor cross section was $\sim 7.7 \times 10^3\text{ A/cm}^2$. Assuming a homogeneous current distribution in the winding cross section, the calculated axial field in the coil center ($z=0, r=0$) is $B_z(z=0, r=0)=80.4\text{ mT}$ and at the center of the inner turn of the coil is $B_z(z=0, r=20\text{ mm})=145\text{ mT}$ at 154 A.

The YBCO tape used in the pancake tape coil is exposed to a strongly inhomogeneous magnetic self-field.⁴ Using a small active area Hall probe we measured B_r in the radial direction at a small distance of $\sim 0.5\text{ mm}$ from the coil just outside the windings ($z=5.5\text{ mm}$). The radial distribution of $B_r(z=5.5)=f(r)$ measured at room temperature and 77 K for

several values of dc currents is shown in Fig. 1. For com-

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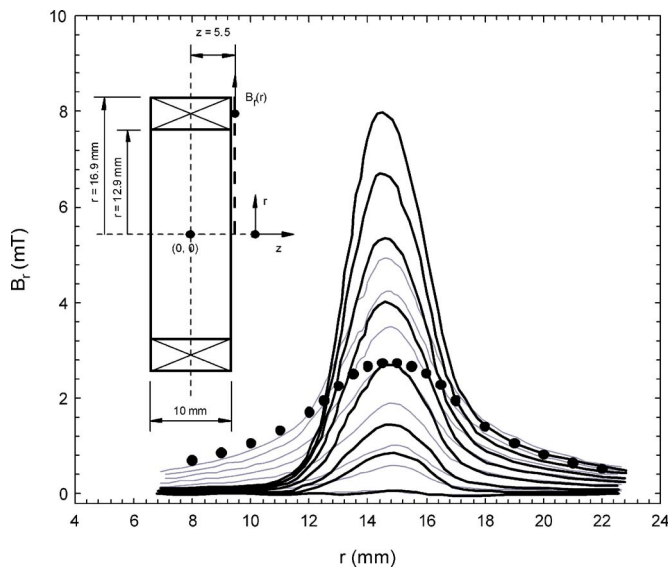


FIG. 1. The field component B_r vs the radial coordinate, r , in the distance of 0.5 mm from the coil: at 300 K (gray lines), measured at coil currents of 6, 5, 4, 3, 2, 1, 0.5, and 0 A (from the top to the bottom), at 77 K (black lines), measured at the same coil currents. (●) calculated values at 5 A assuming uniform current distribution. Inset: the winding geometry.

parison, the distribution of $B_r(z=5.5)$ calculated for a current of 5 A which assumes a uniform current density in the windings is also shown in Fig. 1. The radial component $B_r(r)$ reaches a maximum, $B_{r,max}$, in the middle of the winding at $r=15$ mm. Experiments with larger coil currents and also with ac currents showed that the position of this maximum does not depend on the amplitude and frequency of the current. At 77 K the values for $B_{r,max}$ are much larger than those measured at room temperature, as well as the calculated value. This is a clear indication of the nonuniform current density caused by the induced screening currents.

The variation of $B_{r,max}$ with the triangular shaped current wave $I=0 \rightarrow I_m \rightarrow 0 \rightarrow -I_m \rightarrow 0$ at 77 K is shown in Fig. 2. In the inset we show $B_{r,max}(I)$ measured at room temperature

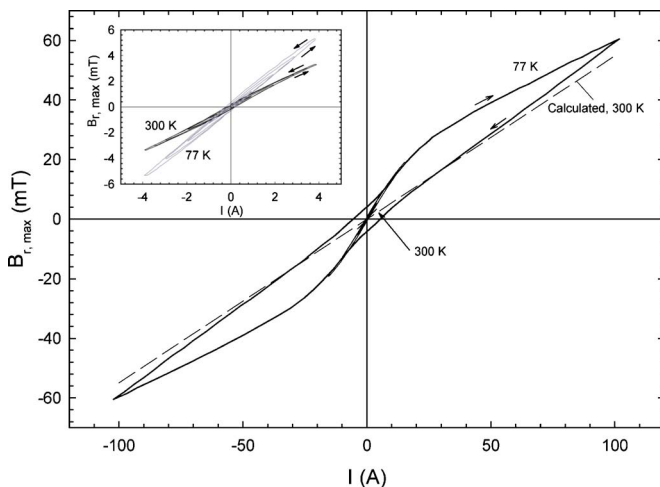


FIG. 2. The maximum of the radial field component, $B_{r,max}$, measured at 77 K for the full dc current waves $0 \rightarrow 100 \text{ A} \rightarrow 0 \rightarrow -100 \text{ A} \rightarrow 0$. The dashed line shows the calculated values assuming the uniform current distribution. The rate of change for dI/dt is $\sim 5 \text{ A/s}$. The inset shows the shape and hysteresis of the curves $B_{r,max} = f(I)$ measured at 300 and 77 K. Note the change of the character of the hysteresis observed at 77 K and at small currents compared with that for the large current (the curve branch down is below the curve branch up).

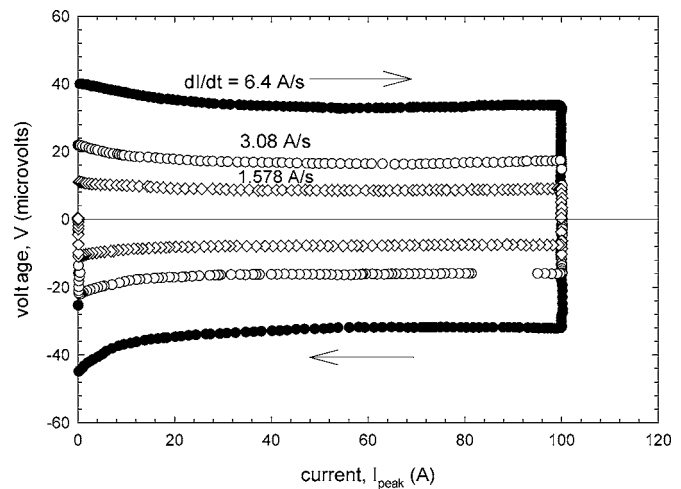


FIG. 3. Coil voltage measured vs coil current for triangular current waves with $dI/dt=6.4 \text{ A/s}$ (●), 3.08 A/s (○), and 1.578 A/s (◇).

and 77 K with several smaller current amplitudes (the small current amplitudes were chosen to avoid the coil heating). The curves at room temperature as well as at 77 K have a clearly visible nonlinear and hysteretic feature. The calculated $B_{r,max}$ values are lower than the measured ones. The character of the hysteresis of $B_{r,max}(I)$ curves at 300 K is different from that at 77 K. This indicates the influence of the ferromagnetism of Ni+4% W substrate on the magnetic field in the coil winding. According to Ijaduola *et al.*,¹³ the substrate material has a Curie temperature of $\sim 360 \text{ K}$ and the magnetization in parallel field saturates at $H \approx 1000 \text{ Oe}$, which is above the values reached with our coil.

To determine the coil inductance, L , we recorded the coil voltage, V , while applying triangular transport current waves with the amplitude of 50 A at frequencies of 50, 100, and 200 mHz (Fig. 3). With $V=LdI/dt$, the shape of the curves shows that L depends on the current at low current values, ranging from $\sim 7 \mu\text{H}$ at $I=0$ to $\sim 5 \mu\text{H}$ with increasing currents. At higher currents, L is current independent which independence tends to shift to higher current levels as dI/dt increases. The decrease of the inductance with increasing current indicates again an influence of the magnetic properties of the substrate material.

Loss measurements for the YBCO coil at frequencies from 60 to 1000 Hz are shown in Fig. 4. Also shown are the losses in the Cu coil with dc currents and ac currents at frequencies of 100 and 1000 Hz. There is a little difference in losses in the Cu coil between the dc and ac at 100 Hz. At 1000 Hz, the losses in the copper coil also contain a measurable eddy current contribution. The total losses of the YBCO coil increase proportional to I^n , where $n \approx 1.7$ at a frequency of 60 Hz and $n \approx 1.9$ at 1000 Hz. The losses of the copper coil are proportional to I^2 as predicted by theory. However, considerable heating of the Cu coil was observed at larger currents as deduced from the $V-I$ curve, 8.9 K at $I=100 \text{ A}$.

At 60 Hz, the losses in the YBCO coil are nearly two orders of magnitude lower than the Cu coil. With increasing frequency, the YBCO coil losses increase and approach the Cu coil losses, but are still smaller at 1000 Hz. The main components of loss in the YBCO are the hysteresis and self-field losses. Of particular interest are the nonsinusoidal voltages measured at higher currents, as seen in the inset in Fig. 4. The heating of the YBCO coil was monitored by a

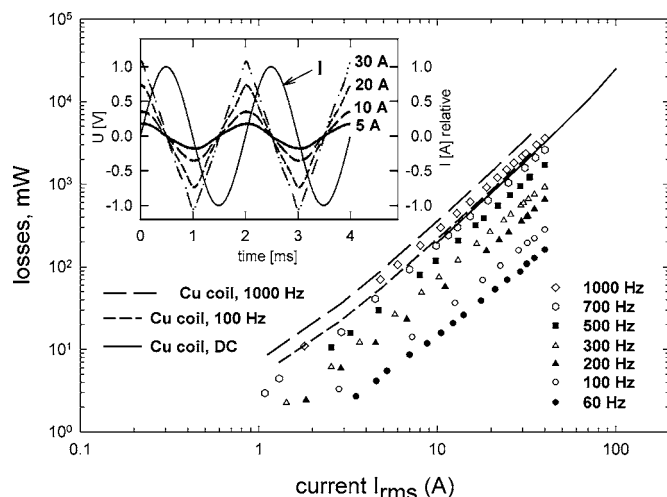


FIG. 4. The measured total ac losses of the YBCO and Cu coils as a function of the coil current I_{rms} at various frequencies from 60 Hz (bottom curve) up to 1000 Hz (upper curve). The losses of Cu coil were measured with dc current (—) and with ac current at 100 Hz (---) and 1000 Hz (—). The inset shows the coil voltage, V , vs time measured at various current I_{rms} at 500 Hz.

copper-Constantan thermocouple installed in the winding and was negligible; at 1000 Hz and $I_{\text{peak}}=50$ A, the temperature increase was below 0.2 K.

In summary, we measured the ac losses in a small YBCO pancake coil and a similar coil made of plain copper tape. We have found that the ferromagnetic substrate significantly influences the coil's magnetic field. As a consequence of the substrate and the induced magnetization currents, the YBCO coil inductance depends on the coil current. At 60 Hz, the losses of the YBCO coil were nearly two orders of magnitude lower than those in the Cu coil. With increasing frequency, this difference becomes smaller, but the YBCO coil still exhibited lower losses at 1000 Hz although indicates the

need for a more ac tolerant architecture for the YBCO conductor. At a rms current of 40 A and 1000 Hz the coil showed a stable operation, the losses were ~ 4 W at 77 K. The measured radial component of the magnetic field showed that the transport current distribution in the windings is highly nonuniform. This indicates a need for the development of ac loss models more suitable for inhomogeneous fields.

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